

Cranial Vault Morphometry for Forensic Sex Estimation: From Traditional Cranial Chords to Three-Dimensional Computed Tomography, Geometric Morphometrics and Artificial Intelligence

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ABSTRACT

Background: Sex estimation is a fundamental component of forensic anthropological analysis because establishing the probable biological sex of unidentified remains substantially narrows the pool of possible identities. The cranium is particularly valuable because of its durability and the presence of numerous sexually dimorphic features. Cranial vault morphology can be assessed using traditional osteometric techniques, radiographic methods, computed tomography (CT), three-dimensional reconstruction and increasingly sophisticated computational approaches.

Objective: This review examines the development and current application of cranial vault morphometry for forensic sex estimation, with particular emphasis on frontal, parietal and occipital cranial chords, three-dimensional computed tomography, geometric morphometrics, discriminant analysis, machine learning and population-specific standards.

Methods: A critical narrative review of published literature was undertaken using peer-reviewed literature indexed in PubMed and other major scholarly databases. Priority was given to original research, systematic and scoping reviews, and contemporary CT-based investigations published predominantly between 2018 and 2026. Earlier landmark studies were retained where necessary to explain the development of cranial morphometric methods.

Findings: Cranial vault dimensions demonstrate measurable sexual dimorphism in many populations, with males generally exhibiting larger cranial dimensions than females. However, the magnitude of dimorphism varies according to anatomical region, population, age, ancestry, measurement technique and analytical approach. Traditional cranial chords provide simple and reproducible measurements, but their diagnostic performance is generally enhanced when multiple variables are combined. Three-dimensional CT and geometric morphometric techniques permit assessment of complex cranial shape and reduce some limitations associated with conventional two-dimensional measurements. Recent studies demonstrate that multivariate discriminant models can achieve high classification accuracy, while machine-learning approaches increasingly permit automated analysis of three-dimensional cranial morphology. Nevertheless, population specificity, external validation, measurement standardization and algorithmic bias remain important concerns.

Conclusion: Cranial vault morphometry remains an important component of forensic sex estimation. Frontal, parietal and occipital measurements can provide useful population-specific information, but no single measurement should be regarded as universally diagnostic. The future of cranial sex estimation lies in integrating standardized CT acquisition, three-dimensional morphometry, robust statistical modelling and independently validated computational approaches. For Nigeria and other African populations, development of large contemporary CT databases and regionally validated equations is particularly important.

Keywords

Forensic anthropology, Sex estimation, Cranial vault, Cranial morphometry, Cranial chords, Computed tomography.

Introduction

Forensic anthropology provides important scientific methods for the examination and identification of human skeletal remains. One of its principal objectives is the development of a biological profile, which commonly incorporates estimation of sex, age, ancestry and stature. Among these characteristics, sex estimation is particularly valuable because it can substantially reduce the number of possible identities associated with an unknown individual [1].

The skull has traditionally been regarded as one of the most informative skeletal elements for sex estimation. Its usefulness is related to its relatively robust structure, high probability of preservation and the presence of multiple morphological and metric characteristics that demonstrate varying degrees of sexual dimorphism [2].

Cranial sexual dimorphism develops through complex interactions between genetic, endocrine, developmental and environmental factors. Male skulls are generally larger and more robust than female skulls, although considerable overlap exists between the sexes. The degree of dimorphism is also not uniform throughout the cranium. Some regions may exhibit pronounced differences whereas others may show relatively weak discrimination [3].

Traditional cranial morphometry has relied extensively on direct measurements obtained from dry skeletal material. Measurements such as maximum cranial length, maximum cranial breadth, bizygomatic breadth, cranial height and various chord measurements have been incorporated into statistical models for sex estimation.

Among these measurements, cranial chords are particularly interesting because they describe the curved dimensions of the cranial vault rather than simply measuring straight-line breadth or height. The frontal chord extends between the nasion and bregma, the parietal chord between bregma and lambda, and the occipital chord between lambda and opisthion. Together, these measurements provide information about the anterior, superior and posterior components of the cranial vault.

The introduction of computed tomography has transformed this field. CT allows researchers to obtain cranial measurements from living individuals, postmortem subjects and archived clinical records without physically manipulating skeletal remains. Three-dimensional reconstruction additionally allows the skull to be viewed from multiple directions and permits digital measurements to be obtained from reconstructed skeletal surfaces [4].

The increasing sophistication of imaging has been accompanied by advances in statistical methodology. Discriminant function analysis, logistic regression and geometric morphometrics have progressively expanded the analytical possibilities. More recently,

machine-learning algorithms and automated computer-vision methods have begun to demonstrate considerable potential for sex estimation from three-dimensional cranial data [5].

A 2022 scoping review emphasized that cranial sex-estimation methods remain highly population-specific and that there is a continuing need to validate existing methods in additional populations [6].

This is particularly important for African populations, where contemporary CT-based reference datasets remain relatively limited compared with European and Asian populations.

The purpose of this review is therefore to examine the development and current evidence surrounding cranial vault morphometry for forensic sex estimation, with particular attention to cranial chords, CT-based assessment, three-dimensional morphometrics, statistical modelling and emerging artificial-intelligence approaches.

Biological Basis of Cranial Sexual Dimorphism

Cranial sexual dimorphism refers to measurable differences in cranial size and shape between males and females.

Several biological mechanisms contribute to cranial dimorphism. Sexual hormones influence skeletal growth during puberty, while differences in muscle development and mechanical loading may influence the morphology of regions associated with muscular attachment. Nutritional status, developmental environment and genetic background can additionally influence cranial size and shape.

However, the biological basis of cranial dimorphism should not be interpreted as producing two completely separate male and female cranial forms. Rather, the distributions overlap, and sex estimation represents a probabilistic classification process.

Milella et al. examined sexual differences in human cranial morphology and emphasized that sexual dimorphism is not equally distributed throughout the skull. Their findings support the concept that some cranial regions are more dimorphic than others and that population-specific models are necessary when describing cranial sexual variation [3].

This observation has important implications for the use of cranial chords. Although the frontal, parietal and occipital regions may all demonstrate sexual differences, their contribution to sex classification may not be equivalent.

Cranial Vault Morphometry

The cranial vault forms the superior and lateral portion of the neurocranium and provides an extensive surface for quantitative assessment.

Common cranial vault measurements include:

- Maximum cranial length;
- Maximum cranial breadth;

- Cranial height;
- Frontal chord;
- Parietal chord;
- Occipital chord;
- Frontal arc;
- Parietal arc;
- Occipital arc;
- Cranial circumference;
- Various interlandmark distances.

These measurements provide information about cranial size and shape.

Traditional measurements are generally obtained using osteometric instruments such as spreading calipers, sliding calipers and anthropometers. Although these methods remain useful, they require physical access to skeletal material.

CT has allowed many of these measurements to be transferred into a digital environment.

Cranial Chords and Their Forensic Significance

Frontal chord

The frontal chord represents the distance between the nasion and bregma along the frontal region of the cranial vault.

Because the frontal bone contributes substantially to the anterior cranial vault, differences in frontal development may contribute to sexual dimorphism.

The frontal region is also associated with other sexually dimorphic characteristics, including the supraorbital region and frontal sinus. However, the chord itself should be distinguished from frontal sinus measurements because they represent different anatomical variables.

Parietal chord

The parietal chord is the distance between bregma and lambda along the midline of the parietal region.

The parietal bones contribute significantly to the superior cranial vault. Differences in cranial expansion during growth may therefore be reflected in parietal measurements.

Occipital chord

The occipital chord extends from lambda to opisthion and represents the posterior component of the cranial vault.

Occipital morphology may demonstrate sex-related differences, although the magnitude of these differences varies across populations.

Importance of measuring multiple chords

One advantage of evaluating frontal, parietal and occipital chords together is that they provide information from different regions of the cranial vault.

A multivariate model can therefore potentially capture complementary aspects of cranial sexual dimorphism.

This principle is supported by contemporary CT studies. Hoshioka et al. evaluated 21 cranial measurements in 263 contemporary Japanese individuals and found that 19 were significantly larger in males. Although individual measurements had classification accuracies ranging from 57.8% to 88.2%, a seven-variable multivariate model achieved 93.9% accuracy [7].

The finding illustrates that combining multiple cranial dimensions can produce substantially better classification than relying on one measurement alone.

Traditional Osteometry versus CT-Based Morphometry

Traditional osteometry has contributed extensively to forensic anthropology. Direct measurement of skeletal remains remains valuable because it permits direct assessment of the specimen.

However, traditional osteometry has several limitations.

Major limitations include:

1. Limited availability of documented skeletal collections;
2. Potential damage to fragile remains;
3. Difficulties accessing certain landmarks;
4. Observer-dependent landmark placement;
5. Inability to reconstruct damaged regions;
6. Limited availability of contemporary reference samples.

CT addresses several of these limitations.

CT datasets permit researchers to:

- Manipulate digital images;
- View anatomy in multiple planes;
- Create three-dimensional models;
- Repeat measurements;
- Archive datasets;
- Perform retrospective studies.

The increasing application of CT in forensic anthropology has therefore created an important bridge between radiology, anatomy and forensic science.

Computed Tomography and Three-Dimensional Cranial Analysis

Three-dimensional CT reconstruction represents a major development in cranial morphometry.

The skull can be reconstructed as a digital three-dimensional model, allowing anatomical landmarks to be identified and measured in a virtual environment.

The principal advantages include:

Multiplanar visualization

Researchers can examine anatomical structures in sagittal, axial and coronal orientations.

Digital measurement

Measurements can be obtained using calibrated digital tools.

Three-dimensional visualization

The skull can be rotated to inspect anatomical landmarks from multiple directions.

Reproducibility

The same digital dataset can be measured repeatedly.

Digital preservation

A CT dataset can be retained for future analysis without further manipulation of skeletal remains. These advantages have encouraged increasing use of CT in forensic anthropology.

Hoshioka et al. demonstrated the utility of 3D CT in a contemporary Japanese sample by obtaining 21 cranial measurements from reconstructed bone-only images [7].

Similarly, Battan et al. used clinical CT data from 217 individuals in Northwest India and evaluated 10 craniofacial variables. Their stepwise discriminant analysis achieved 93.6% classification accuracy [8].

Geometric Morphometrics

Traditional morphometry focuses largely on distances, angles and other predefined measurements.

Geometric morphometrics takes a different approach by analyzing the spatial relationships among anatomical landmarks.

The method allows researchers to separate aspects of shape from overall size and can identify patterns of morphological variation that may not be captured by conventional linear measurements.

Navega et al. demonstrated the application of geometric morphometric and discriminant approaches to cranial sex estimation. Their work illustrates the potential of combining landmark-based shape analysis with conventional classification techniques [9].

Bertsatos et al. similarly investigated sex-related geometric variation using 80 ectocranial landmarks from modern individuals and demonstrated the usefulness of geometric approaches for identifying informative cranial dimensions [10].

Geometric morphometrics may therefore be particularly useful when cranial shape differences are more informative than isolated linear dimensions.

Three-Dimensional Interlandmark Distances

An important development in CT-based cranial morphometry is the derivation of large numbers of interlandmark distances from three-dimensional datasets.

Small et al. used 45 homologous landmarks from 227 South

African crania and mathematically derived 990 interlandmark distances. They developed discriminant functions for different cranial regions and obtained cross-validated accuracies ranging from 71.8% for the orbital region to 88.2% for the global cranium [11].

The importance of this study lies in its demonstration that three-dimensional datasets can generate measurements beyond conventional caliper-based variables.

This approach is particularly relevant to fragmented skulls because regional models may allow sex estimation even when the complete cranium is unavailable.

Evidence for Sexual Dimorphism in Cranial Measurements

The available literature generally demonstrates that males tend to exhibit larger cranial dimensions than females.

However, the strength of the difference varies.

Milella et al. emphasized that sexual dimorphism varies among cranial regions and that the degree of variation within each sex is also important [3].

Battan et al. reported statistically significant sexual differences across all 10 selected craniofacial variables in their Northwest Indian CT sample, with the length of the cranial base identified as the strongest single sexually dimorphic variable [8].

Hoshioka et al. reported that 19 of 21 measurements were significantly larger in males in a contemporary Japanese sample [7].

These findings support the general biological pattern of larger male cranial dimensions but also emphasize that the specific measurements providing the strongest discrimination differ among populations.

Statistical Approaches to Cranial Sex Estimation

Independent-samples t-test

The independent-samples t-test is commonly used to determine whether the mean value of a cranial measurement differs significantly between males and females.

It is useful for identifying sexually dimorphic variables.

However, statistical significance alone does not establish forensic usefulness.

A measurement can demonstrate a highly significant p-value while still producing substantial overlap between male and female distributions.

Therefore, classification accuracy and effect size should be considered in addition to statistical significance.

Discriminant Function Analysis

Discriminant function analysis remains one of the most frequently used approaches for sex estimation.

A discriminant function combines measurements into an equation capable of assigning an individual to one of two or more predefined groups.

The general form is:

$$D = a + b_1X_1 + b_2X_2 + b_3X_3$$

where:

- D = discriminant score;
- a = constant;
- b = coefficient;
- X = cranial measurement.

A sectioning point is subsequently used to classify individuals.

The principal advantage of discriminant analysis is that it permits several measurements to be considered simultaneously.

Battan et al. demonstrated this clearly: univariate, multivariate and stepwise analyses produced accuracies of 88.9%, 91.7% and 93.6%, respectively [8].

Hoshioka et al. similarly found that their seven-variable model achieved 93.9% accuracy, substantially exceeding the performance of most individual measurements [7].

These findings support the use of multivariate approaches when sufficient sample sizes are available.

The Importance of Cross-Validation

A major issue in forensic morphometry is the tendency for classification accuracy to appear higher when a model is evaluated using the same observations used to construct the model.

This is known as apparent or original classification accuracy.

Cross-validation provides a more realistic estimate of model performance.

For example, a model may correctly classify 95% of the training observations but perform substantially less well on new individuals.

Therefore, forensic studies should ideally report:

- Original classification accuracy;
- Leave-one-out cross-validation;
- Independent external validation;
- Sensitivity;
- Specificity;
- Confidence intervals.

Failure to provide validation can lead to overestimation of the forensic usefulness of a model.

Population Specificity

Population specificity represents one of the most important considerations in forensic cranial morphometry.

Cranial morphology varies among populations because of genetic background, developmental environment, nutrition and other biological factors.

The 2022 scoping review concluded that cranial and odontological sex-estimation methods are highly population-specific and require validation in additional populations [6].

This principle is particularly important when applying equations developed in European or Asian populations to African individuals.

For example, the Japanese study by Hoshioka et al. produced a highly accurate seven-variable model within its contemporary Japanese sample [7]. However, this does not mean that the same equation should automatically be applied to Nigerian remains.

Similarly, models developed in India, Europe or South Africa require appropriate validation before application to Nigerian populations.

African Evidence

African populations remain underrepresented in many international forensic anthropological datasets.

This represents an important limitation because cranial morphology demonstrates population variation.

South African studies have contributed substantially to the development of African reference standards.

Small et al. developed three-dimensional interlandmark functions using South African crania and demonstrated that regional and whole-cranium models can be used for sex estimation [11].

The importance of these studies extends beyond South Africa because they demonstrate the value of developing contemporary African skeletal standards rather than relying exclusively on equations developed from non-African populations.

For Nigeria, the need for population-specific data is particularly important because the country contains considerable regional and ethnic diversity.

Nigerian Evidence

The Nigerian literature on CT-based cranial sex estimation is expanding.

Jaafar et al. investigated craniofacial dimensions using CT images from Kaduna State and analyzed 399 cranial scans comprising 236 males and 163 females [12].

The study demonstrates the feasibility of using routine clinical CT

archives to develop Nigerian forensic reference standards.

The user's present research involving 518 CT scans from Edo and Delta States similarly illustrates the potential of large contemporary Nigerian CT datasets.

The use of 258 male and 260 female scans provides a relatively balanced sex distribution and permits robust comparison between the groups.

However, the results should be interpreted as regional reference data, rather than automatically representing the entire Nigerian population.

This distinction is crucial when developing forensic equations.

Cranial Vault Morphometry in the Context of Nigerian Forensic Anthropology

The Nigerian forensic context presents several opportunities for CT-based cranial morphometry.

Routine hospital CT archives contain large numbers of contemporary cranial images. When appropriately anonymized and ethically approved, these datasets can provide valuable sources of reference information.

Potential measurements include:

- Frontal chord;
- Parietal chord;
- Occipital chord;
- Maximum cranial length;
- Maximum cranial breadth;
- Cranial height;
- Bizygomatic breadth;
- Orbital dimensions;
- Foramen magnum dimensions;
- Mastoid measurements;
- Cranial-base measurements.

The development of combined Nigerian datasets could allow researchers to determine whether:

1. A national equation is appropriate;
2. Regional equations are necessary;
3. Sex-estimation models differ among Nigerian populations;
4. CT-derived measurements outperform conventional radiographic measurements;
5. 3D shape analysis provides additional discriminatory information.

Machine Learning and Automated Cranial Sex Estimation

The field is increasingly moving beyond conventional statistical models.

Machine-learning algorithms can analyze multiple variables simultaneously and may detect complex patterns that are difficult to capture with traditional linear methods.

Bertsatos et al. developed an automated method using 3D cranial models and computer-vision/machine-learning approaches. Their study used Czech and Greek samples and examined features from the glabella, supraorbital ridge, occipital protuberance and mastoid process. Population-specific accuracies for individual features ranged from 78.5% to 96.7%, while combined multi-feature classification exceeded 91% [5].

This represents an important transition from manually selected measurements toward automated morphological analysis.

Machine learning may therefore provide three important advantages:

- Automated landmark recognition;
- Simultaneous analysis of large numbers of variables;
- Identification of complex nonlinear patterns.

However, these advantages must be balanced against the risk of algorithmic overfitting and population bias.

Artificial Intelligence and Three-Dimensional Cranial Morphology

Artificial intelligence is increasingly being applied to forensic imaging.

AI-based systems may potentially analyze the entire cranial surface rather than relying on a predetermined set of measurements.

This approach could permit automated classification based on:

- Surface morphology;
- Shape;
- Curvature;
- Landmark relationships;
- Volumetric characteristics;
- Regional differences.

Recent studies demonstrate that the field is moving toward automated 3D analysis.

However, AI systems require very large and representative training datasets.

A model developed exclusively from European or Asian CT data may perform poorly when applied to African individuals.

Therefore, African representation in AI training datasets is essential.

Advantages of Cranial Chord Measurements

Cranial chords have several practical advantages.

Simplicity

They are relatively straightforward to define and measure.

Reproducibility

Clearly defined landmarks can facilitate repeated measurements.

Low equipment requirement

Once a CT dataset is available, digital measurement can be performed using imaging software.

Anatomical coverage

Frontal, parietal and occipital chords represent different regions of the cranial vault.

Compatibility with statistical modelling

They can readily be incorporated into discriminant and regression models.

Potential application to archived CT datasets

They can be measured retrospectively without recalling patients.

Limitations of Cranial Chord Measurements

Despite their usefulness, cranial chords have limitations.

First, they primarily represent linear dimensions and may not completely capture complex three-dimensional cranial shape.

Second, landmark identification may vary among observers.

Third, the degree of sexual dimorphism differs among populations.

Fourth, age-related changes and developmental differences may influence cranial measurements.

Fifth, a model developed from one population cannot automatically be generalized to another.

Sixth, extremely high classification accuracy requires careful independent validation because apparent accuracy may be inflated by overfitting.

For these reasons, cranial chords should ideally be incorporated into a broader morphometric framework.

Measurement Error and Reliability

Measurement error is a fundamental concern in cranial morphometry.

Potential sources include:

- Incorrect landmark placement;
- Inappropriate CT plane;
- Image distortion;
- Inadequate image resolution;
- Observer fatigue;
- Software differences;
- Reconstruction parameters.

Studies should therefore report intra-observer and inter-observer reliability.

Common statistical measures include:

- Intraclass correlation coefficient;

- Technical error of measurement;
- Relative technical error of measurement.

Battan et al., for example, reported technical measurement-error assessments in their CT-based craniofacial study, strengthening the methodological evaluation of their model [8].

Future Nigerian studies should similarly incorporate formal measurement-error analysis.

Methodological Recommendations for Future Studies

Future research should adopt standardized protocols covering:

CT acquisition

- Slice thickness;
- Reconstruction interval;
- Reconstruction algorithm;
- Field of view;
- Matrix size;
- Patient positioning.

Measurement

- Precise landmark definitions;
- Standardized anatomical planes;
- Calibrated software;
- Repeated measurements.

Statistical analysis

- Descriptive statistics;
- Effect sizes;
- Appropriate significance tests;
- Discriminant analysis;
- Cross-validation;
- External validation;
- Sensitivity and specificity.

Computational analysis

- Transparent machine-learning methods;
- Independent test datasets;
- Population-specific evaluation;
- Reporting of model uncertainty.

Major Research Gaps

The literature identifies several important research gaps.

Limited African reference datasets

African populations remain underrepresented in international cranial morphometric databases.

Limited Nigerian multicentre datasets

Most Nigerian studies remain institutionally or regionally focused.

Limited validation between Nigerian regions

It remains unclear whether an equation derived from southern Nigeria will perform equally well in northern or eastern Nigerian populations.

Lack of standardized CT protocols

Differences in CT acquisition can influence measurements.

Limited external validation

Many studies rely predominantly on internal classification accuracy.

Limited AI research using African datasets

Machine-learning studies using African cranial CT data remain relatively uncommon.

Critical Discussion

The literature strongly supports the existence of cranial sexual dimorphism, but the evidence does not support the concept of a universally superior cranial measurement.

The principal strength of cranial chord measurements is their simplicity. Frontal, parietal and occipital chords are anatomically understandable, relatively easy to measure and suitable for incorporation into statistical models.

However, the simplicity of these measurements can also be considered a limitation. Cranial morphology is fundamentally three-dimensional, and a small number of linear measurements may fail to capture the complete morphological differences between male and female crania.

This explains the increasing interest in geometric morphometrics and three-dimensional CT.

The progression from conventional measurements toward 3D shape analysis is therefore not a replacement of traditional anatomy but an extension of it.

A particularly important lesson from recent studies is that **multivariate analysis generally provides stronger classification than isolated measurements**. Battan et al. demonstrated increasing classification performance from univariate to multivariate and stepwise discriminant analysis [8]. Hoshioka et al. similarly demonstrated that a seven-variable model substantially outperformed individual measurements [7].

However, high classification accuracy should always be interpreted cautiously.

A model achieving 99% accuracy in its development sample is not necessarily a model that will achieve 99% accuracy in an independent forensic population.

External validation is therefore critical.

The same issue applies to artificial intelligence. AI may identify complex patterns that are invisible to conventional measurements, but the algorithm is only as representative as the dataset used for training.

For Nigeria, this creates both a challenge and an opportunity.

Nigeria possesses large numbers of clinical CT examinations that could potentially support contemporary forensic reference databases. Properly anonymized CT datasets from multiple regions could be used to establish population-specific equations and subsequently test whether national or regional models provide superior performance.

Recommendations for Nigerian Research

Based on the current evidence, the following priorities are recommended for Nigeria:

1. Establish multicentre CT-based cranial databases.
2. Include multiple Nigerian geographical regions.
3. Use standardized CT protocols where possible.
4. Develop precise landmark definitions.
5. Assess intra- and inter-observer reliability.
6. Compare linear morphometry with geometric morphometrics.
7. Incorporate three-dimensional CT analysis.
8. Perform external validation.
9. Compare discriminant analysis with machine-learning algorithms.
10. Develop Nigerian-specific forensic reference equations.
11. Investigate whether regional equations outperform a national model.
12. Establish transparent AI datasets containing representative Nigerian populations.

Conclusion

Cranial vault morphometry remains an important component of forensic sex estimation. Traditional measurements such as frontal, parietal and occipital chords provide useful quantitative information regarding cranial sexual dimorphism and can be incorporated into discriminant models for population-specific sex estimation.

The development of computed tomography has substantially expanded the possibilities of cranial morphometry by providing non-invasive, high-resolution and three-dimensional representations of the skull. Geometric morphometrics has further extended analysis from simple distances toward complex patterns of cranial shape.

Recent research demonstrates that multivariate models generally outperform individual cranial measurements, while automated three-dimensional and machine-learning approaches provide promising new possibilities. Nevertheless, high classification accuracy should not be interpreted without considering sample size, population composition, measurement error, validation procedures and model generalizability.

The most important lesson from the current literature is therefore that cranial sex estimation is population-specific and probabilistic. No single cranial chord, measurement or algorithm can be expected to provide universal accuracy across all populations.

For Nigeria, there is a particular need for contemporary, multicentre and population-specific CT reference datasets. Integration of cranial anatomy, three-dimensional CT, geometric morphometrics, conventional statistics and carefully validated artificial intelligence could establish a stronger scientific foundation for forensic sex estimation in Nigerian and other African populations.

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